Analysis of Marine Boundary Layer Aerosol Fields Obtained Using Multi-Wavelength Scanning Lidar Systems

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LONG-TERM GOALS

Our long-term goal is to improve our understanding of dynamics of marine aerosols and water vapor fields in the coastal marine boundary layer using a scanning lidar and meteorological parameters.

OBJECTIVES

Our scientific objectives are to collect lidar data sets that can be used to improve and develop models of the aerosol optical properties in the coastal marine boundary layer (MBL). Various aerosol models exist (e.g., Fitzgerald, 1989; Edson et al., 1999), but few are appropriate for coastal regions. We are studying the vertical aerosol structure in the lowest part of the atmosphere directly above the ocean surface.

APPROACH

We are using a scanning multi-wavelength lidar to measure the 4-D (space and time) aerosol optical fields in order to characterize the aerosol properties in a marine setting (Sharma et al., 2001). These measurements have been carried out at Bellows Air Force Station next to the University of Hawaii's Meteorological Tower (21^o 21.848' N, 157^o 42.584' W). We are able to study the spatial structures of the aerosol scattering fields out to distances of up to 10 km from the shore. The scanning lidar data enables us to compare the aerosol properties measured by the shore-based instruments with larger scale coastal aerosol scattering fields. Dr. Shiv Sharma is the project director involved in all aspects of these efforts. Dr. Barry Lienert has developed the software and supervises the data collection. Dr. John Porter is involved in calibration and modeling of the data.

WORK COMPLETED DURING 2003

1. Two of our SEAS research papers have been published.
2. We have processed multi-wavelength lidar data to derive particle size information.

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3. We have impemented a correction for the lateral movement of aerosol by the wind during
a two-dimensional scans.
4. We have analyzed the Bellows lidar scans to study the variation in plume height with wind speed.
5. We have implemented Fast Fourier transformation and averaging of horizontal lidar returns.
6. We have developed a novel approach to derive quantitative extinction values for a moving lidar platform.
7. We have tested a small portable lidar for field measurements of lidar elastic backscatter.
8. We have also tested a small portable Remote Raman Lidar for analysis of chemical species.

RESULTS

Wavelength Dependence of Extinction

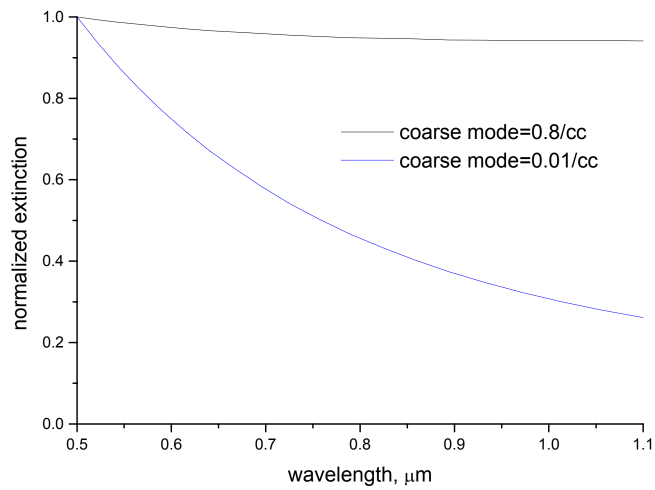

Figure 1. Variation of extinction with wavelength calculated using Mie theory for aerosol models.

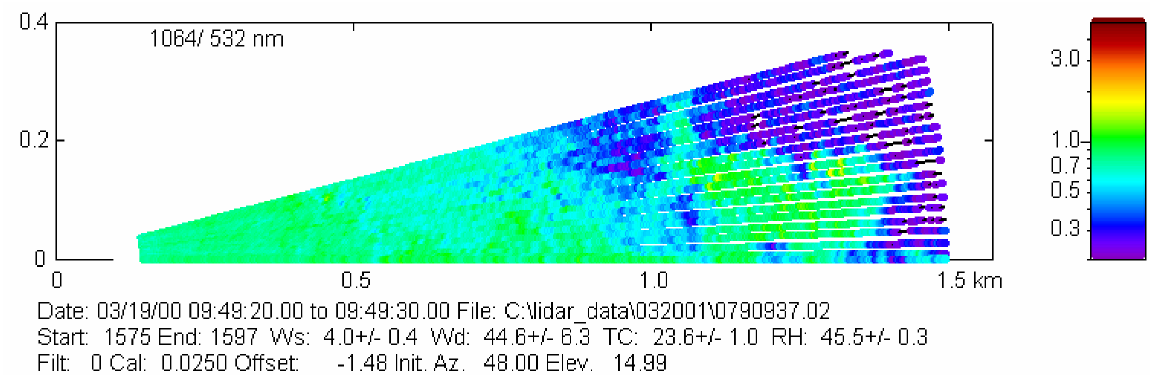

Figure 2. Extinction ratio scan at Bellows Beach on 3/20/01having two different coarse mode concentrations.

To study the wavelength dependence of lidar backscatter we consider a basic example. Figure 1 shows Mie calculation of aerosol extinction for two bimodal size distributions with a fixed accumulation mode (radius=0.065 µm, width=1.8, concentration=400/cc in number) and a coarse mode

(radius=1.0 µm, width=2.8) with two different concentrations. For the smallest coarse mode (blue curve), the extinction has strong wavelength dependence. For the largest coarse mode concentration, there is little wavelength dependence. Wavelength dependence, such as shown in Fig. 2, could therefore be explained by a predominance of accumulation-mode aerosol.
In processing our lidar data (at 0.532 µm wavelengths) we adjust the lidar parameters to obtain quantitative aerosol scattering coefficients using the horizontal calibration method (Porter et al., 2000). This works well for 0.532 µm channel but not for the 1.064 µm channel. In order to calibrate the 1.064 µm channel we have adjusted the lidar and aerosol properties so that the ratio (1.064/0.532 extinction) is close to one for large particles (dense spray plumes) which is in agreement with the calculations shown in Fig. 1. Once this has been done, the lidar ratios display specific features suggesting areas of large and small particles. The location of these features (see Fig. 2) is consistent with the notion that salt spray plumes (with large particles) rise from the surface while sinking clean air from aloft carries smaller particles. For example, large particle plumes are often observed over reefs at a range of 1.2-1.5 km from the lidar. The blue regions are areas where smaller aerosol sizes dominate. In this approach we have assumed that the total transmission is close to one (due to short ranges involved) and therefore the accumulated error, due to incorrect values of the lidar ratio, is small. The lidar ratio scan shown in Figure 2 are for a day with light winds and with more convective thermals. On light wind days such as this the surface salt plumes were found to rise higher elevations (up to 700 m) consistent with buoyant convection (Sharma et al., 2001).

Power Spectra Of Lidar Data

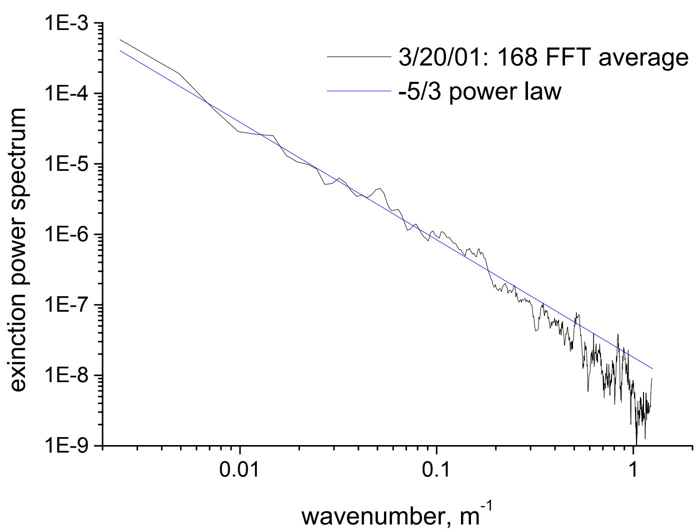

Figure 3. Average power spectrum of 168 horizontal lidar returns (0.2-2.6 km).

In order to investigate the spectral characteristics of lidar data we have Fourier Transformed multiple lidar traces having ranges from 0.2 to 2.6 km. Figure 3 shows one example. The average power spectra are shown for 168 horizontal lidar traces (~5m above sea level) on a day having low wind speeds (1-2 m/s at the surface). Below wave numbers of 0.2 (wavelength>30 m), the power spectrum approximately follows the -5/3 power law (Kolmogorov, 1941, Tsuge, 2002). Above this, the slope steepens, indicating that viscous processes may be becoming predominant. The -5/3 power law dependence implies that the Reynolds number (ratio of turbulent to molecular viscosity) exceeds $4x10^4$ (Tennekes and Lumley, 1972).

Dependence of Plume Height on Wind Speed

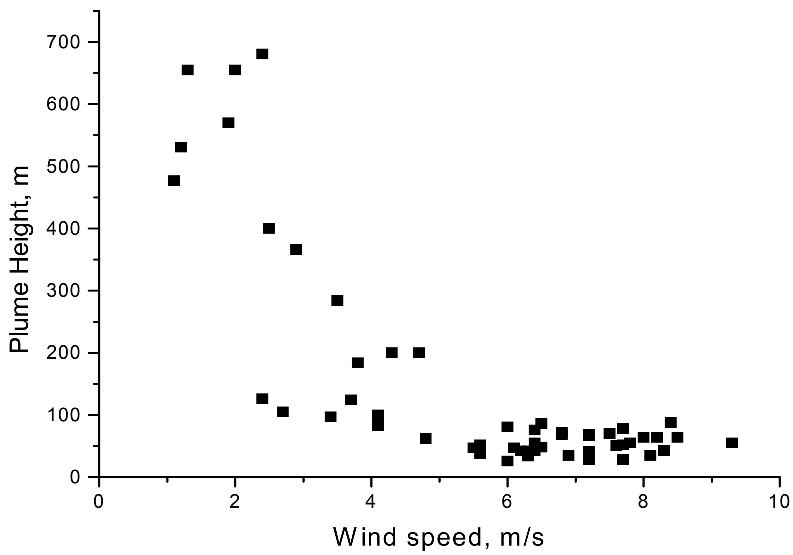

Figure 4. The vertical extent of surface salt plumes generated from breaking waves as observed in our 2-*D lidar scans.*

We investigated the dependence of the height of salt spray plumes from breaking waves on wind speed by visually estimating their height in 2-D lidar scans. Fig. 4 shows a significant decrease in plume height when the wind speed exceeds 5 m/s. This may be due to enhanced surface heating under light wind conditions.

Miniature Lidar Measurements

Our small portable Mie-Rayleigh lidar system was first described in Porter et al. (2002). Fig. 5 shows the lidar system. It uses a 12.7cm-diameter telescope mounted on a two-axis scanning motor. A 20 Hz pulsed Nd:YAg laser (pulse energy 12 mJ at 0.532 µm) provides the excitation The laser beam diameter is ~3 mm and has a divergence of 0.7 mrad. The 0.532 µm backscatter signal is detected by a miniature photo-multiplier tube, while the 1.064 µm signal is detected by an avalanche photo-diode. The detector signals are amplified using custom 50-MHz logarithmic amplifiers (Lienert et al, 2002), which increase the dynamic range and voltage resolution. Digitization and averaging are performed with an eight-bit digital oscilloscope, with the output supplied to a laptop computer via a serial link. The data is processed and displayed in real time on laptop computer using custom software. We have evaluated the performance of the system by studying meteorological processes in the marine atmosphere (Porter et al., 2002). Lidar measurements clearly show the height of the mixed layer (near the surface) and the trade wind inversion. Figure 6 shows an example of this where we have collected lidar measurements while driving around the southeastern shore of Oahu on a day with strong trade wind conditions (~15 m/s). It can be seen that on this day the sea salt was mixed throughout the mixed layer (up to ~500 m height) with average aerosol scattering coefficient values of 10^{-4} m^{-1} with some higher scattering values near Makapuu Beach where we drove close to breaking waves. In Fig. 6, clouds appear as dark areas where the inferred scattering coefficient values are larger than $1x10^{-3}$ m^{-1}.

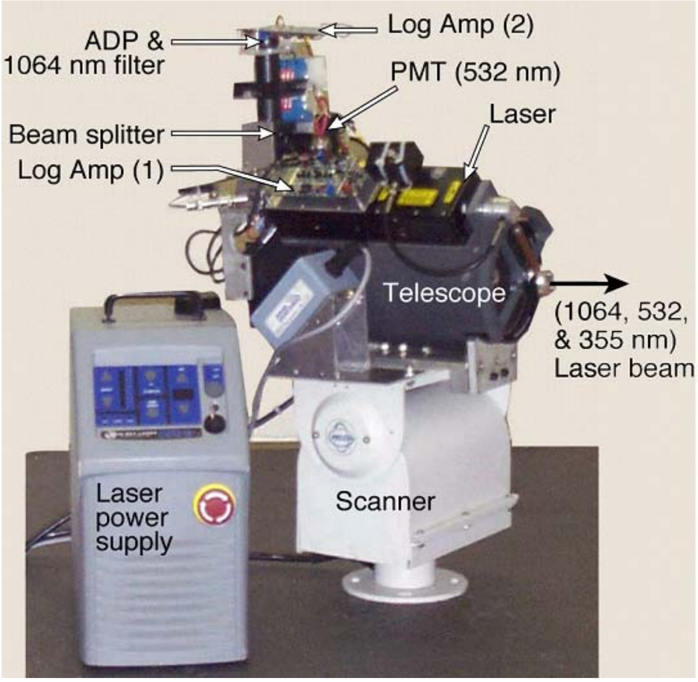

Figure 5. The small lidar system showing the telescope, laser, scanner and detectors.

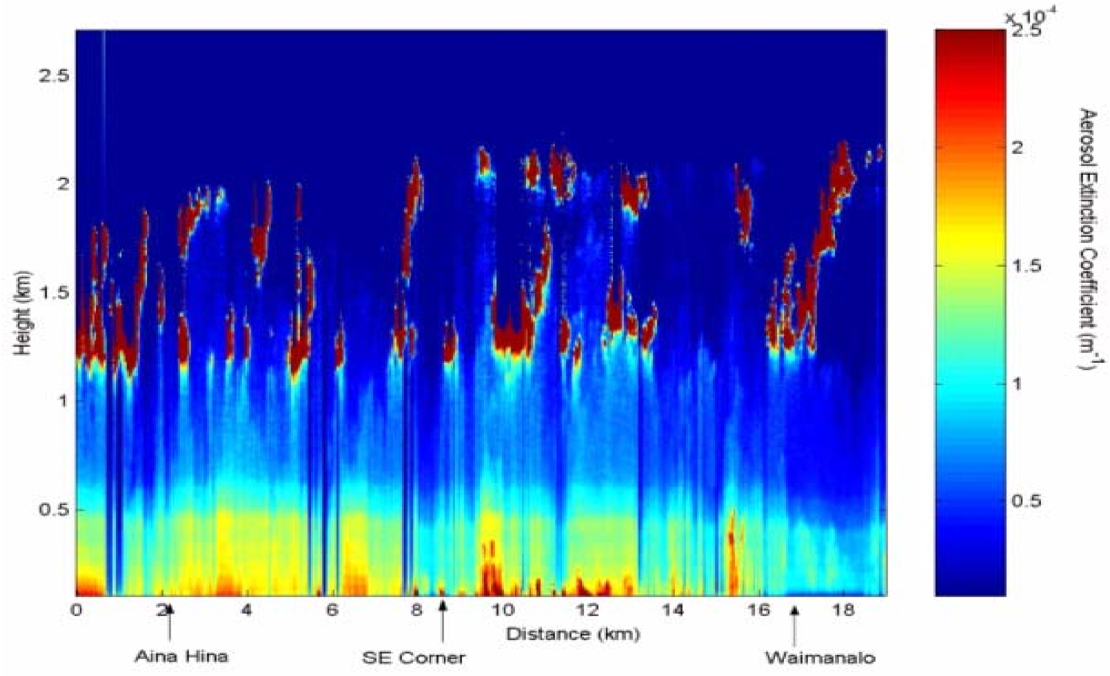

Figure 6: Vertical lidar extinctions measured around the Southeastern shore of Oahu.

In this high wind case the mixed layer is well below the cloud base with an intermediate layer between the mixed layer and the cloud layer. It is also interesting to note that the aerosol optical concentrations are roughly the same on the windward and leeward sides of the island on this windy day.
In order to convert the lidar measurements into quantitative aerosol extinction values, simultaneous sun photometer measurements were also carried to obtain the column aerosol optical depths. The aerosol scattering coefficients converted to optical depths and compared with the sun photometer values. Here we have assumed that the sea salt aerosol is dominant and that it is non-absorbing. The sun photometer measurements were carried out with a sun photometer that was calibrated at the Mauna Loa Observatory using a Langley Plot approach. As expected for large sea salt aerosols (Fig. 1), the aerosol optical depths are spectrally independent. The magnitude of the optical depths (~0.15) was quite large for sea salt but is not unexpected for such windy conditions. Typical clean trade wind conditions (wind speeds of 7 m/s) have aerosol optical depths near 0.05 (Porter et al., 2001).

IMPACT/APPLICATIONS

1. The wavelength dependence of our lidar data demonstrate the predominance of small aerosols close to the surface outside of the salt spray plumes. This unexpected result has important implications for EM wave transmission in the marine boundary layer.
2. The finding that the power spectra of aerosol scattering follows a -5/3 power law has important implications for applications that utilize EM propagation in the lower marine boundary layer.
3. The miniature lidar system could find use in many applications where portability is essential.

TRANSITIONS

We supplied the source code of our lidar software to Dr Christine Merck at the Max Planck Institute in Munich, to assist in determining atmospheric properties for a large telescope in the Canary Islands. We also supplied the program to Sarah Masonis at the University of Washington, who used it to display our 2-D lidar scan data as part of an ONR-funded project.

RELATED PROJECTS

We have continued our cooperation with Dr. Clarke's ONR-funded aerosol properties group by supplying them with our data. We have also been working with Dr John Madey (UH Physics Dept.) in a DOE-funded project to remotely detect nuclear testing residuals.

REFERENCES:

Edson, J. et al., Coupled Marine Boundary Layers and Air-Sea Interactions Initiative: Combining Progress Studies, Simulations, and Numerical Models, ONR Report, Aug 25, 1999, Revision 5.0, pp 139.

Fitzgerald, J.W., 1989: Model of the aerosol extinction profile in a well-mixed marine boundary layer, *Appl. Opt.*, **28**, 3534-3538.

Kolmogorov, A.N., 1941. The Local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers, *Dokl. Akad. Nauk SSSR,* **30**, p 301. Reprinted in *Proc. R. Soc. Lond A,* **434**, 9-13. (1991).

Lienert, B., J. N. Porter, S. K. Sharma, N. Ahlquist and D. Harris, 2001: A 50 MHz Logarithmic Amplifier for use in Lidar Measurements, *J. Atmos. Ocean. Tech.,* **19**, 654-657, 2002.

Porter, J.N., Lienert, B., S.K. Sharma (2000) Using the Horizontal and Slant Lidar Calibration Methods To Obtain Aerosol Scattering Coefficients From A Coastal Lidar In Hawaii, *J. Atmos. Oceanic Technology*, **17**, 1445-1454.
Porter, J, Miller, M., Pietras, C. (2001): Ship-Based Sun Photometer Measurements Using Microtops Sun Photometers, *Journal of Atmospheric and Oceanic Technology*, **18**, 765-774.
Porter, J.N., B. Lienert, S. K. Sharma, and H. W. Hubble (2002), A Small Portable Mie-Rayleigh Lidar System to Measure Aerosol Optical and Spatial Properties, *J. of Atmospheric and Oceanic Tech.*, **19**, 11, 1873-1877.
Sharma, S. K., B. R. Lienert and J. N. Porter, 2001: Scanning Lidar Measurements of Marine Aerosol Fields At A Coastal Lidar Site in Hawaii. *Proceedings of the SPIE Lidar Remote Sensing for Industry and Environment Monitoring*, Sendai, Japan, SPIE vol. **1453**, 159-166.
Tsuge, S., 2001, http://www.ca-homes.com/science/tsuge-8/
Tennekes, H. and J.L. Lumley (1972). *A First Course in Turbulence*, Mass. Inst. Techn., 293pp

PUBLICATIONS

B. R. Lienert, J. N. Porter, and S. K. Sharma, Aerosol Size Distributions from Genetic Inversion of Polar Nephelometer Data, J. Ocean. Atmos. Tech., 20,. p 1403–1410, 2003.

J. N. Porter, B. R. Lienert, S. K. Sharma, E. Lau, and K. Horton, Vertical and Horizontal Aerosol Scattering Fields over Bellows Beach, Oahu, during the SEAS Experiment. J. Ocean. Atmos. Tech., 20, p 1375–1387, 2003.

Porter, J.N., S.K. Sharma, B. R. Lienert, E. Lau and K. Horton, Vertical and Horizontal Aerosol Scattering Fields Over Bellows Beach, Oahu During the SEAS Experiment, J. Atmos. Oceanic Technol., 20, 1375-1387, 2003.

A. Clarke, V. Kapustin, S. Howell, K. Moore, B. Lienert, S. Masonis, T. Anderson, and D. Covert, Sea-Salt Size Distributions from Breaking Waves: Implications for Marine Aerosol Production and Optical Extinction Measurements during SEAS, J. Ocean. Atmos. Tech., 20, p1362–1374, 2003

Porter, J.N., Obtaining Quantitative Aerosol Extinction Values From An Aircraft Forward Looking Lidar, (submitted to Applied Optics, 2003).

Multi-wavelength Scanning Lidar Measurements of the Effect of Wind Speed on Marine Aerosol Fields Generated by Breaking Waves, S. K. Sharma, B. R. Lienert, and J. N. Porter, Lidar Remote Sensing for Industry and Environment Monitoring III, Hangzhou, China 24-25 October 2002,

Proceedings of SPIE Vol. #4893, 12pp.
Sharma, S.K., J. N. Porter, A. K. Misra, H. W. Hubble and Premlata Menon, Portable stand-off Raman and Mie-Rayleigh Lidar for Cloud, Aerosols, and Chemical Monitoring, SPIE, San Diego, 2003. Lidar Remote Sensing for Environmental Monitoring IV, Conference 5154, San Diego, CA., 3-4 August 2003, *Proceedings of SPIE* Vol. #5154, 15 pp.